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NONLINEAR FLUX FLOW IN SINGLE CRYSTAL NIOBIUM

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ABSTRACT

The consequences of a low Ginzburg-Landau κ are noted in the behavior of a high purity single crystal of niobium. The flux flow voltages are not explained by the Kim Anderson theory. A modification to the theory is proposed, and its implications are discussed.

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SUMMARY

The flux flow properties of a single crystal sample of niobium, with a value of κ near unity, are investigated. Marked differences, both from high κ flux flow behavior and from other niobium results, are observed in highly nonlinear current-voltage measurements. The sample was chemically polished and vacuum annealed to remove anomalous results interpreted as having originated in a strained surface layer. No general relation between the current, voltage, and magnetic field could be found, although at low current densities the current dependence of the voltage appears to be a power law, as observed previously. At higher currents or very near the critical field there are pronounced deviations from this simple relation.

The behavior is discussed in terms of the conditions affecting the motion of the flux lines in low κ materials as opposed to that in high κ materials. Working within the framework of the established flux flow theory, it is shown that the behavior is consistent with the conjecture that some of the flux lines may remain pinned while others may move. An appropriate modification to the flux flow theory is developed for the low κ materials. The result suggests that it is possible to deduce directly from the flux flow characteristics the spectrum of pinning sites within a material.

INTRODUCTION

The nature of flux flow and flux creep related effects in type II superconductors has been the subject of extensive research. However, most studies to date have been concerned with materials for which the Ginzburg-Landau κ parameter is large compared to unity. For these materials the theories of references 1, 2, and 3 adequately account for most of the experimental observations. In contrast, flux motion effects in those type II superconductors for which $\kappa \sim 1$ have received little attention in the literature.

The experiments reported on here involved a niobium sample in single crystal form. The properties of this crystal were such that its κ was 1.3. Thus, the mean free path length Λ was of the same order of magnitude as the coherence distance ξ. The purpose of the research was to study flux motion in a material having a κ near the limiting value for type II superconductivity (i.e. near $\kappa = 0.707$).

PROCEDURE

A thin slab sample (dimensions $0.97 \times 0.91 \times 0.05$ cm) was spark cut from a triply zone refined rod of single crystal niobium. The crystal was cut so as to make the faces of the slab parallel to the [100] direction. To remove the surface damage introduced by the spark cutting, the sample was chemically polished in a solution of equal parts of HNO_3, HF, and H_2O. This reduced the thickness of the slab to 0.03 cm. Finally, the sample was vacuum annealed by electron bombardment heating at 1800° to 1900° C in 10^{-7} torr for 25 hours.

The electrical properties of the sample were obtained both before and after the chemical-polish - anneal treatment. A slight increase was noted in the resistance ratio R(300K)/R(4.2 K) from 61.4 to 77.7 after final treatment. More remarkable, though, were the changes that occurred in the superconducting properties. In particular, there was a significant drop in the upper critical field H_{c2}. (H_{c2} was determined magnetically by the two-coil technique described in reference 4.) Whereas H_{c2} had been 1.10 tesla for the as-spark-cut state, its value after the polish-anneal treatment was reduced to 0.330 tesla. This later figure compares favorably with the one derived from

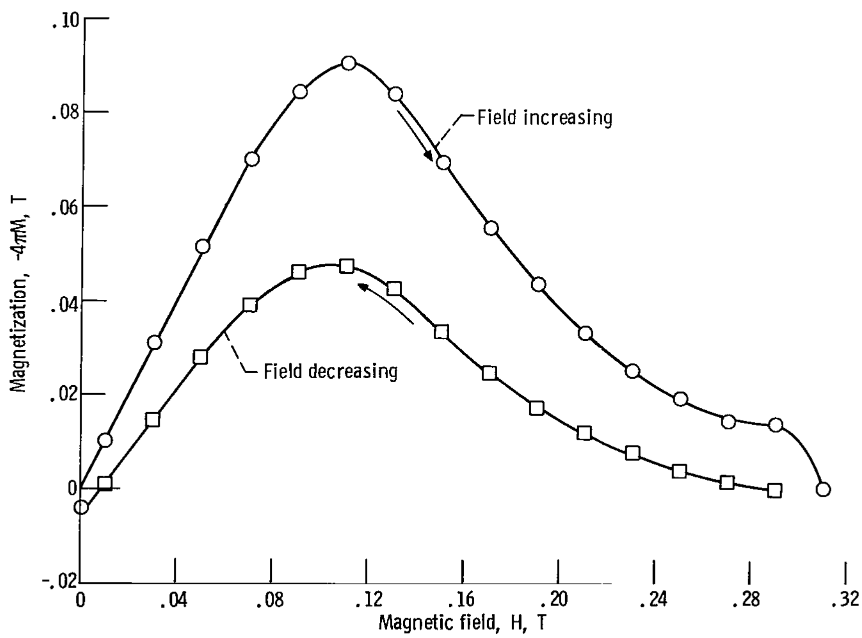

Figure 1. - Magnetization against applied magnetic field for niobium single crystal.

the magnetization curve (fig. 1) of the sample. The method used for measuring the magnetization is described by Skinner (ref. 5). Indicated in figure 1 is an H_{c2} of 0.310 tesla. These curves also indicate a lower critical field H_{c1} of 0.110 tesla, and a thermodynamic critical field H_c calculated to be 0.166 tesla. A κ of 1.3 was calculated from the critical fields ($\kappa = H_{c2}/(\sqrt{2}\, H_c)$). This change in the superconducting properties and others are discussed in the following section.

Measurements of the longitudinal flux flow voltages were made using the conventional four contact configuration. The slab was oriented with the magnetic field perpendicular to both the slab face and to the current. The resistive transitions were obtained by recording the potential drop across the sample at constant magnetic field while slowly increasing the current.

RESULTS

Shown in figure 2 are the voltage-current characteristics of the sample in the as-spark-cut state. Here the response is a family of straight lines with slopes all equal to the normal state resistance. Raising the background field serves only to induce the resistive transition at a lower current. That this behavior is associated with the spark-damaged surface is evidenced by its disappearance following the chemical-polish - anneal treatment. After the treatment the sample responded as shown in figure 3. Apparently, spark cutting the sample left the surface in a highly strained condition - a condition that increases the critical field and current parameters of a material. This produced a sandwich-like structure to the sample with the unstrained interior being enclosed between surface layers of higher critical currents and fields. In a magnetic

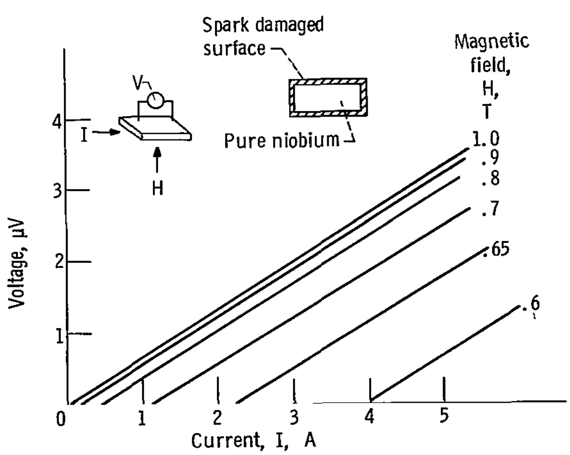

Figure 2. - Voltage - current response before chemical polishing and vacuum annealing.

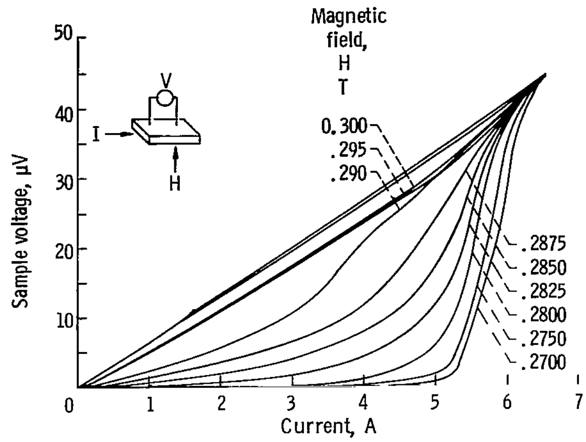

Figure 3. - The resistive transition from onset of resistance to point where voltage becomes asymptotic to Ohm's law.

field, then, the interior of the sample could be normal while its surfaces were superconducting and carrying a transport current. Under these circumstances no voltage appears across the sample. However, when forced to conduct currents greater than the critical currents of the surfaces, the sample shunts the excess into the interior. The resistive voltage therefore originates from the current flow in the already normal interior region.

Chemically polishing and annealing the sample removed the influence that the spark-damaged surfaces had on the response. The resistive transition of the unstrained niobium could then be traced from its onset to the point at which the voltage became asymptotic to the Ohm's law line (fig. 3). It was possible to follow the transitions in a quasi-static manner primarily because of the reduced flux pinning present in the sample. Furthermore, the flat plate geometry of the sample allowed the power dissipated by the moving flux lines to be effectively transferred to the helium bath without significantly heating the sample. Ordinarily, the flux flow heating produced in most materials (especially those with a high κ) triggers a spontaneous transition to the normal state. In those cases, observation of a quasi-static transition is not possible.

There are two limiting experiments with which to compare the results presented in figure 3. The first is the work on high κ materials (reference 2) which shows a linear current-voltage relation in flux flow experiments. The second comparison is with the work of Wasim and Zebouni (ref. 6), also on a niobium plate sample, but at lower fields and much lower current densities. The comparison with these experiments may be made by replotting the data of figure 3 logarithmically as shown in figures 4 and 5. First, the data for low current densities (total current below 2 A) is shown in figure 4. For the region between 0.2925 and 0.2825 tesla, the region studied by Wasim and Zebouni, the current and voltage are related by the expression $V \alpha I^N$. The exponent

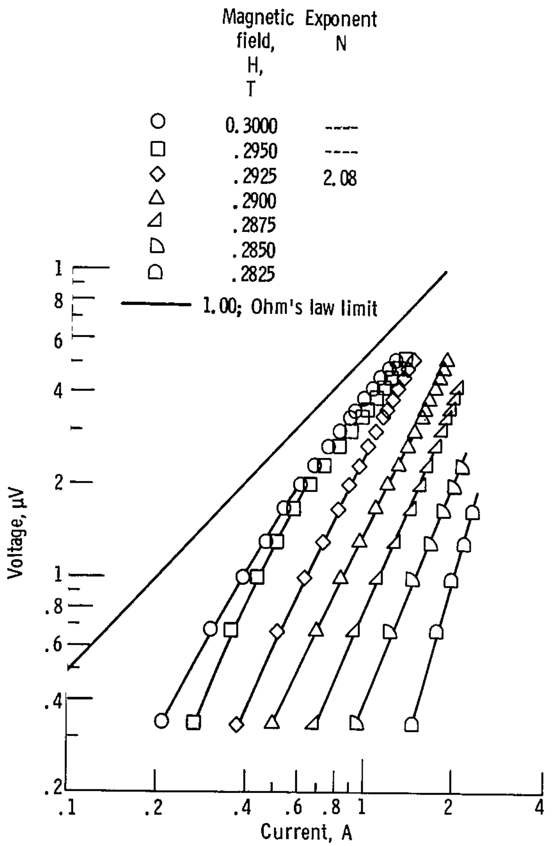

Figure 4. - Flux flow voltage against transport current at various magnetic fields. Low-current region.

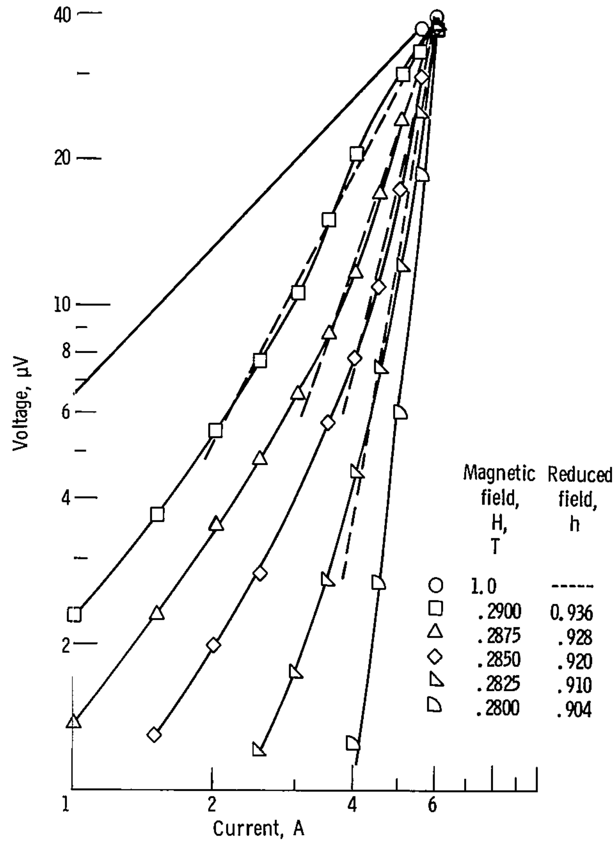

Figure 5. - Flux flow voltage against transport current at various magnetic fields. High current region; reduced temperature, $t = T/T_c = 0.457$; upper critical field, $H_{c2} = 0.310$; reduced field, $h = H/H_{c2}$.

varies with magnetic field and has values between 2 and 3.7, while the flux flow theory of reference 2 would predict $n = 1$. These data, up to a reduced field ($h = H/H_{c2}$) of 0.936 agree qualitatively with that of Wasim and Zebouni, although the exponents differ. The curve of reference 6 for for $h = 0.93$ has $n = 1.1$ while the $h = 0.936$ line of figure 4 gives $n = 2.0$. For higher values of the reduced field, there is a marked deviation from linearity, even at these low currents, which is not noted by Wasim and Zebouni. It should be noted that in this region the nearly equal spacing between the curves implies that $V \alpha e^H$.

When the log V against log I data are replotted for the entire current range of the experiment, even stronger differences from the earlier work appeared. The curves are highly nonlinear for all fields between $h = 0.904$ and the Ohm's law limit. The dashed lines represent crude straight line fits to the data near the transition point. It is seen that the exponents of the lines vary strongly from $n = 1.8$ to $n = 9.4$ for reduced fields between 0.936 and 0.904.

DISCUSSION

The nonlinear (voltage-current) curves observed for niobium (fig. 3) and the linear curves of the alloys (ref. 2) may result directly from differences in κ. In alloys, and in general for materials with $\kappa >> 1$, there are two factors which strongly restrict the motion of the flux lines. One is related to the formation of flux bundles. The fact that it is energetically unfavorable for the flux density to vary appreciably over distances less than the penetration depth λ (ref. 1) gives the lines a spatial rigidity. This rigidity results from the establishment of a lattice-like structure of flux lines within the bundle. The structure extends over a distance of approximately λ, the bundle diameter. Thus, it may require that only one flux line within a bundle be pinned for the entire bundle to become pinned.

In general, a bundle is subject to a pinning force that is the net effect of all the pinning sites in the volume occupied by the bundle. A very strong pinning site, though, can pin a whole bundle as long as its pinning force is greater than the Lorentz force $J \cdot \varphi_B$ where J is the transport current density and φ_B is the flux in the bundle. In effect, then, the formation of flux bundles increases the range of the pinning sites from crystal defect size (assumed to be ξ in size) to λ, the size of the flux bundle. Hence, the formation of flux bundles increases the number of flux lines which can be pinned by each site.

The second factor restricting the motion of the flux lines is related to the nature of the pinning sites. It is true that materials for which $\kappa >> 1$ have intrinsically a greater density of pinning sites than do low κ materials. Typically, the dislocation density in alloys is found to be of the order of 10^{12} per square centimeter (ref. 7). By comparison, the dislocation density in pure niobium can be as low as 10^{2} per square centimeter (ref. 8). If the dislocations are assumed to be themselves the primary pinning agents, then at the very least the density of pinning sites is equal to the dislocation density.

Compare this primary-site density now to the density of flux lines present in the material. The upper limit on the flux line density is H_{c2}/φ_0, where φ_0 is the flux quantum (2×10^{-11} tesla cm^2). Taking NbZr alloy wire as an example, with H_{c2} = 6 tesla, the maximum flux line density is 3×10^{11} lines per square centimeter. Hence, in this case and in general for $\kappa >> 1$, there are always more pinning sites than there are flux lines. Furthermore, a bundle that might become unpinned could not move if the spacing between pinned bundles was not large enough for it to slip past.

These properties of the $\kappa >> 1$ materials make it very difficult for any flux to move unless the entire flux structure within the material moves. The agreement between the flux flow theory (ref. 1) and the experimental findings on high κ materials is consistent with this hypothesis because in the theory all the flux lines are assumed to be moving.

The situation is different in low κ materials. For these materials the penetration depth λ is comparable in magnitude to the coherence distance ξ. This implies that the size of the bundle is comparable in magnitude with that of the individual lines. Thus, as κ approaches the 0.707 limit, the number of flux lines per bundle approaches unity. With the defects or pinning sites assumed to be ξ in size, each pinning site can pin essentially only one flux line directly. This gives the flux lines a relative freedom to respond individually to pinning disturbances. The influence of the strongest pinning sites is thereby greatly reduced over what it might be if κ were large.

Not only are the flux lines freer with $\kappa \sim 1$, they are also subject to less pinning. This is because the dislocation density in low κ materials is so much lower. As previously indicated, the dislocation density in niobium can be as low as 10^{2} per square centimeter (ref. 8). With a lower dislocation density the flux lines can move past one another more easily. But more importantly, note the ratio of the dislocation density to the flux line density. In niobium, for example, the flux line density may rise to $H_{c2}/\varphi_0 = 1.5\times10^{10}$ lines per square centimeter (H_{c2} = 0.3 tesla). It is apparent that the flux lines exceed the pinning sites in number. In such a situation there are always some lines free to move. And in the presence of a transport current these lines are in a state of flux flow.

A pinned flux line can be freed if the Lorentz force on it is sufficiently large to overcome the free energy barrier of the pinning site. Allowing for a spectrum of pinning strengths among the sites, the number of flux lines in motion at a given field then will increase with the Lorentz force as the individual pinning potentials are exceeded. It is suggested that the voltage-current response of niobium (fig. 3, p. 4) is governed by a variable number of flux lines in motion - a number that increases with increasing current (Lorentz force).

In light of the differences between high and low κ materials, the question is raised as to how the established flux flow theory might be modified for the low κ case. The principle consideration here is that the flux lines act individually rather than as part of a bundle. The theory must therefore allow for a variable (Lorentz force dependent) number of moving flux lines.

As in the Kim-Anderson theory, a transport current density J imposes on the individual flux lines a Lorentz force of

$$F_L = J\varphi_0 \tag{1}$$

per unit length. Opposing the Lorentz force on a moving flux line is what is purported to be a viscous drag force of

$$F_D = \eta\nu \tag{2}$$

per unit length; η is a viscosity parameter and ν is the flow velocity. The assumption is that the pinning sites hinder the motion of the flux lines, and that the balance between the driving force and drag tendencies results in an equilibrium flow velocity of

$$\nu = \frac{\varphi_0 J}{\eta} \tag{3}$$

Accompanying the motion of the flux lines is a power dissipation that depends directly on the number of moving flux lines. In the original flux flow theory all the flux lines were assumed to be moving. As indicated above, this assumption is good for $\kappa >> 1$, but not for $\kappa \sim 1$. Generally only some fraction of the total number of lines is moving. If N_m is the number of moving flux lines per unit area, then the power dissipated per unit volume is

$$P = N_m F_L \nu \tag{4}$$

N_m is a function of both magnetic field and current. To maintain the flux flow requires a power input density equivalent to

$$P = VJ \tag{5}$$

where V is the voltage per unit length across the sample. Therefore, the observable voltage per unit length resulting from the flux flow is

$$V = \frac{N_m \varphi_0^2 J}{\eta} \tag{6}$$

The implications of equation (6) are consistent with the qualitative explanation made previously of the niobium behavior. The voltage is seen to be directly dependent on the total number of moving flux lines and on the transport current. Its field dependence is implicit in N_m.

It is interesting also that through equation (6) it is possible in principle to determine the number strength spectrum of the pinning sites (i.e., the number of pinning sites with a particular pinning strength). Consider a sample in a constant magnetic field. The total density of flux lines in the sample, N_T, is assumed to be only a function of the field, and is therefore constant. However, the density of moving flux lines, N_m, can vary with J (i.e., Lorentz force). From equation (6) N_m is given by

$$N_m = \frac{\eta V}{\varphi_0^2 J} \tag{7}$$

Thus since

$$N_T = N_m + N_p \tag{8}$$

where N_p is the density of pinned flux lines, it follows that

$$\frac{dN_m}{dJ} = -\frac{dN_p}{dJ} \tag{9}$$

In low κ materials it is assumed here that each pinning site can "hold" only one flux line. This assures that a change in the number of pinned lines is accompanied by a corresponding change in the density of occupied sites, N_{sites}

$$\frac{dN_p}{dJ} = \frac{dN_{sites}}{dJ} \tag{10}$$

Thus as the Lorentz force is increased by dF_L, the density of occupied sites changes by

dN_{sites}. Therefore the pinning site density $n(F_L)$ defined as the density of pinning sites of pinning strength F_L per unit F_L is given by

$$n(F_L) = -\frac{dN_{sites}}{dF_L} = -\frac{1}{\varphi_0}\frac{dN_{sites}}{dJ} = \frac{1}{\varphi_0}\frac{dN_m}{dJ} \tag{12}$$

From equation (7) it follows that

$$n(F_L) = \left(\frac{\eta}{\varphi_0^3}\right)\left(\frac{1}{J}\right)\left(\frac{dV}{dJ} - \frac{V}{J}\right) \tag{13}$$

Equation (13) gives the pinning spectrum in terms of the directly observable current and voltage. Because F_L is a force per unit length, the force exerted by a particular pinning site is the product of the sample thickness times the Lorentz Force. Note that as the normal state is approached, (dV/dJ) becomes equal to V/J, and $n(F_L)$ properly goes to zero.

CONCLUDING REMARKS

This study of niobium has demonstrated that the established flux flow theory cannot be directly applied to low κ superconductors. The behavior of low κ materials, however, is shown to be understandable on the basis that they possess an inherently greater freedom for flux motion. As a consequence, the flux line motion in these materials more strongly reflects the fine structure of the pinning site potentials. Therefore, it would seem that the low κ materials provide the ideal medium in which to investigate the influences of the pinning spectrum on the superconducting critical current and magnetic field and on factors affecting flux stability. Certainly a better understanding of the control that the pinning sites have on the dynamics of the flux flow is needed. This knowledge would make it possible to deal more effectively with the problems of flux stability in superconductor applications.

Lewis Research Center,
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